The Spaceborne Infrared Atmospheric Sounder (SIRAS) Instrument Incubator Program Demonstration

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***Abstract*—The Spaceborne Infrared Atmospheric Sounder (SIRAS) Instrument Incubator Program (IIP) successfully demonstrated a long wavelength infrared (12 to 15.4 µm) compact grating spectrometer with spectral resolution of approximately 1000. This system incorporated novel, wide-field refractive optics, including hybrid diffractive/aspheric lenses, to achieve a compact, lightweight design. The system was tested at cryogenic temperatures and successfully demonstrated the spectral and throughput performance required. This paper discusses the design, development, and test of the SIRAS spectrometer and potential applications to future Earth Science Missions.**

Keywords: Earth Science, Atmospheric Sounding, SIRAS, AIRS, Infrared, Grating, Spectrometer

I. Introduction

The NASA Instrument Incubator Program (IIP) has sponsored the development of prototype optical hardware to meet the needs of next-generation high-resolution infrared imaging spectroscopy. Additional information is available in the final report for The Spaceborne Infrared Atmospheric Sounder (SIRAS) Instrument Incubator Program [1]. This program has successfully built and tested a very complex high-resolution infrared imaging spectrometer under cryogenic operating conditions in a laboratory environment. This IIP was very successful in that advancements were made in the area of refractive infrared optics and a subsystem was developed that has many applications in future Earth Science Enterprise programs.

II. SIRAS IIP Objectives

This section was taken from the SIRAS IIP proposal and modified to discuss the actual approach used for the IIP. It is worth noting that we did almost everything we proposed to do in the proposal in the way that we said we would. The only exception is the build of an image field scrambler. This requirement was obviated at the system level by the use of scene imaging at much higher spatial resolution. The SIRAS spectrometer meets the requirements of the longer wavelength region of the Atmospheric Infrared Sounder (AIRS) on the Earth Observing System (EOS) Aqua spacecraft.

A. Objectives

SIRAS is well suited to the IIP because the system employs a new optical design utilizing materials and processes that are beyond the state of the art (e.g., diffractive/aspheric infrared optics). A breadboard demonstration of the end-to-end system has validated the technical approach and has provided a measure of the spacecraft resource savings and performance capability of the proposed flight system. The following objectives are defined in the SIRAS IIP proposal:

1) achieves the optical quality and the spectral resolution consistent with the required resolving power, $\lambda/\Delta\lambda$, between 900 and 1400. **Achieved between 900 and 1200**. **Successful**.

2) achieves the optical transfer function (spatial performance) required to perform as an accurate radiometer in the presence of high scene contrast (referred to as the Cij requirement on AIRS). **Achieved by providing a 24x improvement in spatial resolution as compared to AIRS. Successful**.

3) achieves the high optical throughput required to meet the NEdT requirement. **Achieved for most of the spectrum. Roll off seen at low end due to the use of commercial grade background rejection filters. Moderately Successful.**

4) demonstrates a spectrometer system of significantly reduced size, weight, and volume but of comparable performance to that of AIRS. **IIP built to flight mechanical configuration. No issues. Successful.**

The entry point for the SIRAS IIP was Technology Readiness Level (TRL) 3. We had analytically determined that the design was feasible and had the experience of the AIRS program to validate our models. We completed and tested a laboratory breadboard during the course of the program and have completed TRL 5. Testing was performed in the laboratory environment in thermal vacuum at critical cryogenic optical and detector temperatures.

B. *Cost and Schedule Performance*

As expected, technical difficulties were encountered in this hardware development program, particularly with the coating of the high-curvature CdTe lens. This resulted in a schedule delay of approximately four months. Despite the delay, the team managed to meet the original budget with no cost overruns. This effort is a good example of the ability of the Instrument Incubator Program to save flight program costs by developing advanced technology well in advance of program needs.

III. Requirements

JPL has developed a set of requirements for the SIRAS system to meet the AIRS performance capability. The requirements are the result of system design modeling, including spectral and radiometric performance simulations. Table I provides the basic requirements for the SIRAS system for the flight configuration. Spectrometer 4 was chosen for build in this IIP because it is the most challenging due to the long wavelengths. Small variants exist to these requirements as we address the various applications.

TABLE I
Preliminary Design Parameters for SIRAS

Parameter		Spectrometer Number			
		1	2	3	4
λ_{min}	(μm)	3.7	6.2	8.8	12
λ_{max}	(μm)	4.61	8.22	12	15.4
Avg. Sampling	(-)	2200	2200	2200	2200
Avg. Resolution	(-)	1100	1100	1100	1100
Ruling	(μm)	8	14	10	13
Order	(-)	2	2	1	1
λ_{blaze}	(μm)	8.31	14.42	10.40	13.70
Incidence Angle	(deg)	45	45	45	45
Avg. Dispersion	(rads/μm)	0.2677	0.1534	0.1082	0.0832
Field of View	(deg)	13.957	17.752	19.844	16.201
Detector IFOV	(mr)	0.500	0.500	0.500	0.500
Slit IFOV	(mr)	1.000	1.000	1.000	1.000
EFL	(cm)	5.00	5.00	5.00	5.00
F-Number	(-)	1.70	1.70	1.70	1.70
Aperture Size	(cm)	2.94	2.94	2.94	2.94
Resolution.	(mr)	0.1723	0.2991	0.4314	0.5683
Detector Size	(μm)	25	25	25	25
No. Channels	(-)	487	620	693	566
Transmission	(-)	0.5	0.5	0.5	0.5
FPA-Length	(cm)	1.22	1.55	1.73	1.41

SIRAS was born out of the need for a smaller and less costly version of AIRS to be compatible with spacecraft resource requirements for future missions.

The IIP requirements are, therefore, based on meeting the AIRS requirements in their entirety. This includes spectral, radiometric, and spatial performance. The same Low-Earth Orbit (LEO) requirements for the spectrometer apply to the Geo-synchronous Earth Orbit (GEO) system, as will be described later. Changes to the system will occur in the primary telescope, scanner, electronics, and other subsystems; however, the spectrometer is essentially the same. It should be noted that modest tradeoffs between the spectral range and resolution could be made with minimal impact to the spectrometer provided we keep the same number of detectors. This is achieved through selection of grating ruling. We have also determined that one of the four SIRAS spectrometers can be used for atmospheric correction for high spatial resolution Earth scene imagers, like Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), as applied to a future proposed follow-on Earth System Science Pathfinder (ESSP) urban environment sensor called Thermal Remote-sensing of the Urban Environment (TRUE). Finally, SIRAS offers tremendous potential for global CO_2 observations due to its increased spatial resolution (as compared to AIRS). The same spectrometers are required as those used for atmospheric and temperature sounding from LEO and GEO.

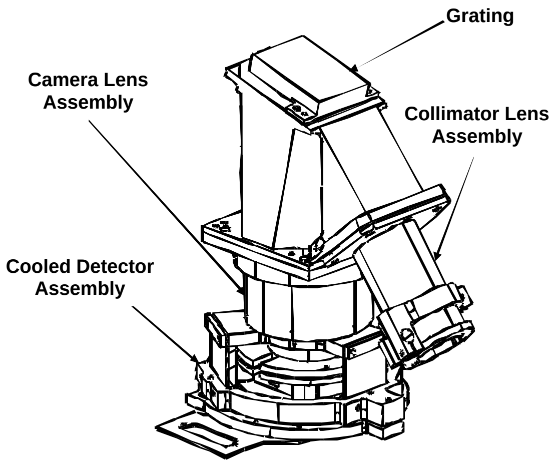
IV. Spectrometer Development

SIRAS represents a new approach for imaging spectrometry in the infrared by combining next-generation wide-field refractive optics with high-dispersion gratings to minimize size and mass. *The result of this IIP is the smallest possible solid-state (no moving parts) IR spectrometer optical system that can be made within the laws of physics (diffraction limited) at these wavelengths and this resolution.* The spectrometer was fully developed and tested under this program and includes all optical and mechanical hardware in a flight-like configuration. The spectrometer is shown in Fig. 1 and covers the wavelength range of 12 to 15.4 μm, with a resolution ($\lambda/\Delta\lambda$) of 900 to 1200. The primary structure measures 10 × 10 × 14 cm and weighs only 2.03 kg. There are no moving parts or metrology lasers.

A. *Technology Advancements*

The SIRAS IIP advanced the state of the art in refractive IR spectroscopy by combining many challenging optical design and fabrication methods to minimize size and mass, particularly in the area of optical component technologies. Technology advancements for SIRAS include:

- **wide-field optics** and **high-dispersion gratings** to minimize aperture size
- **exotic materials with high curvature** to reduce optical transmission losses
- new techniques for **coating high-curvature IR lenses**



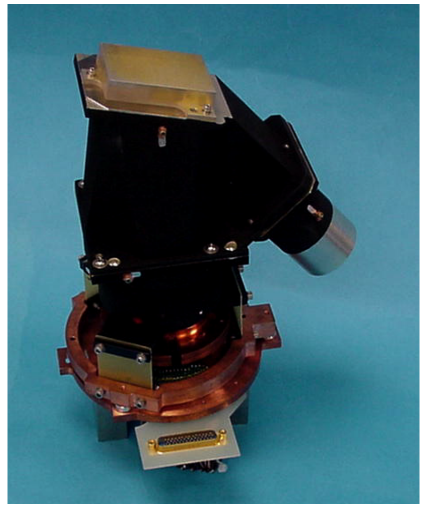


Fig. 1. SIRAS IIP spectrometer design (left) and as-built configuration (right).

- **diffractive/aspheric hybrid surfaces** to minimize lens count and overall mass
- **athermal design** to allow alignment at room temperature and operation at 145 K
- **operation in low orders** to minimize out-of-band rejection filter usage and costs

B. *Optical Design*

The laboratory demonstration spectrometer optical design is shown in Fig. 2. An all-refractive design was selected for the spectrometer because this design form could be developed in a smaller, lower-cost package than an all-reflective design developed to the same requirements. A more detailed description of the optical system is available in the literature [2]. This design form, while not necessarily using the same optical materials, is easily extendable to the other three spectral regions identified in Table 1.

The spectrometer optical system is functionally broken out into three optical subsystems. The collimator intercepts diverging radiation that has passed through the slit and provides collimated radiation to the grating. The grating specified for this application is a linear blazed grating operating at 45° angle of incidence and used in the first diffraction order.

The final optical subsystem is the camera. This refractive lens group serves to image radiation diffracted off the grating onto the focal plane array. The camera requires wide-field imaging. The field is circularly symmetric and design variants of the collimator have been developed to increase the spatial direction field of view to allow a wide-field imaging spectrometer. The wide spatial field allows slower scanning and increases dwell time, thereby allowing high signal-to-noise ratios (SNRs) at high spatial and high spectral resolution.

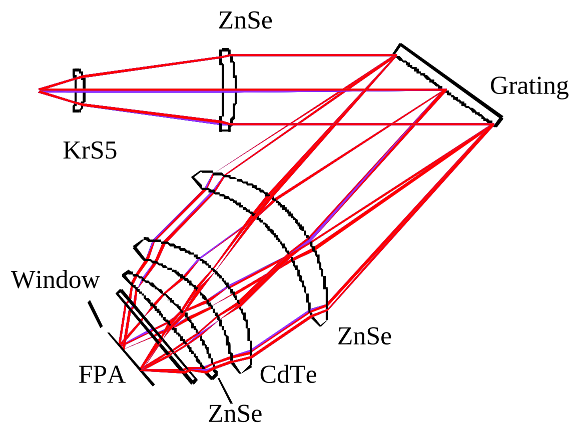


Fig. 2. Optical schematic of the SIRAS spectrometer.

Optical material choices are limited in the 12 to 15.4 μm region, particularly when one wants to get uniformly high transmission over the spectral band. A number of materials that are routinely used in applications in the longwave IR (including germanium and zinc sulfide) were deemed unsuitable because they exhibit excessively high internal absorption at wavelength greater than ~14 μm. It should be noted that, in addition to good transmission, we limited our material selection to those that exhibit reasonably good mechanical, thermal, and handling properties. Therefore, materials such as cesium bromide and potassium bromide were eliminated from consideration. It was readily apparent from lens transmission data that of all the materials considered, zinc selenide, cadmium telluride, and thallium bromoiodide (KrS-5) exhibited the best transmission properties for this spectral region; accordingly, these were the materials selected.

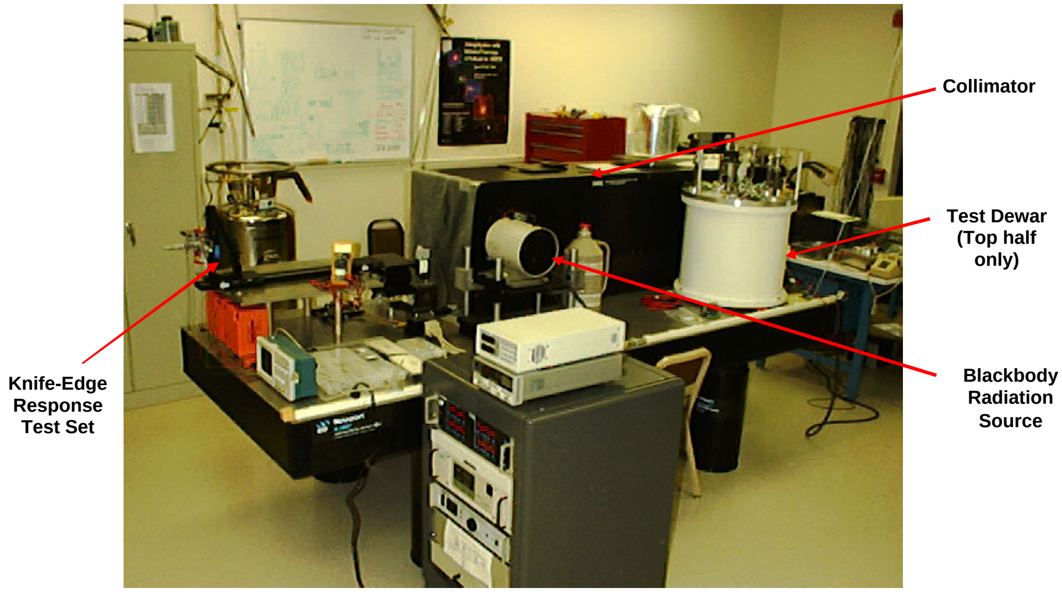


Fig. 3. SIRAS Test Facility included a test dewar, sources, and data acquisition systems.

The SIRAS spectrometer operates at 140 K to reduce background radiation; therefore, the thermal properties of the optical materials must be accounted for because it is desirable that the spectrometer remains in focus from ambient to operational temperature. As such, we set a goal to develop the refractive optical subsystems as athermal systems. This was achieved for the collimator but not the camera, necessitating a focus adjustment of approximately 0.43 mm when going from ambient to 140 K.

V. Testing Facility

The SIRAS test facility is shown in Fig. 3. All hardware development and testing was performed at Ball Aerospace and Technologies Corporation (BATC) in Boulder, Co. The test facility consists of optical sources, the test dewar (which contained the spectrometer), cryogenic control systems, and electronic data acquisition systems. The laboratory breadboard consists of the entire optical chain for the very-long-wavelength spectrometer. In keeping with the IIP objectives, the breadboard has been built to the flight optical and mechanical design configuration. A 165 × 2 element PV HgCdTe multiplexed detector array was be provided on loan from the AIRS program and used to sense the spectra. Interface electronics for the focal plane assembly (FPA) were provided by BAE SYSTEMS on loan to BATC for the IIP program. Computer interface electronics and software were developed by BATC for capture of the data onto a PC.

Cryogenic cooling of the detector array was supplied by a laboratory liquid cryogen fluid loop. The entire system was operated in a BATC vacuum chamber at cold temperatures (approximately 145 K) to limit the background flux falling on the detectors during testing. Sources were viewed through a window (see Fig. 4) and include a collimator for spatial performance tests and a blackbody for radiometric performance testing. Spectral measurements were made by adjusting the path length in air between the window and the blackbody and measuring the CO_2 absorption peaks.

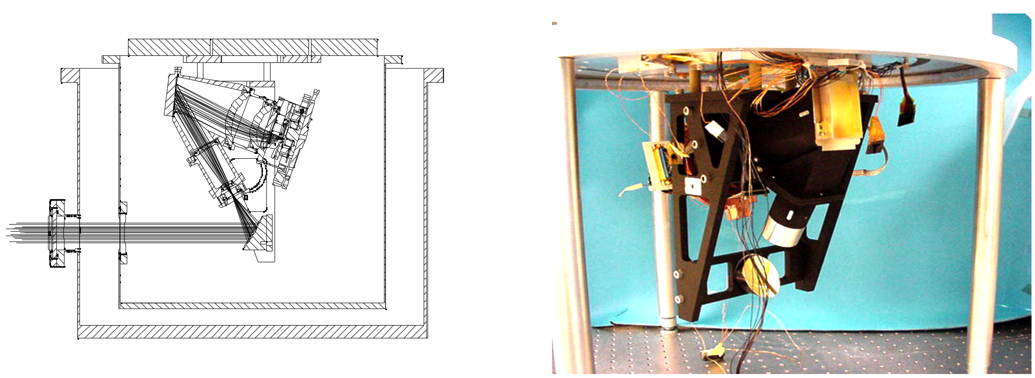


Fig. 4. SIRAS in test dewar: design (left) and as-built (right).

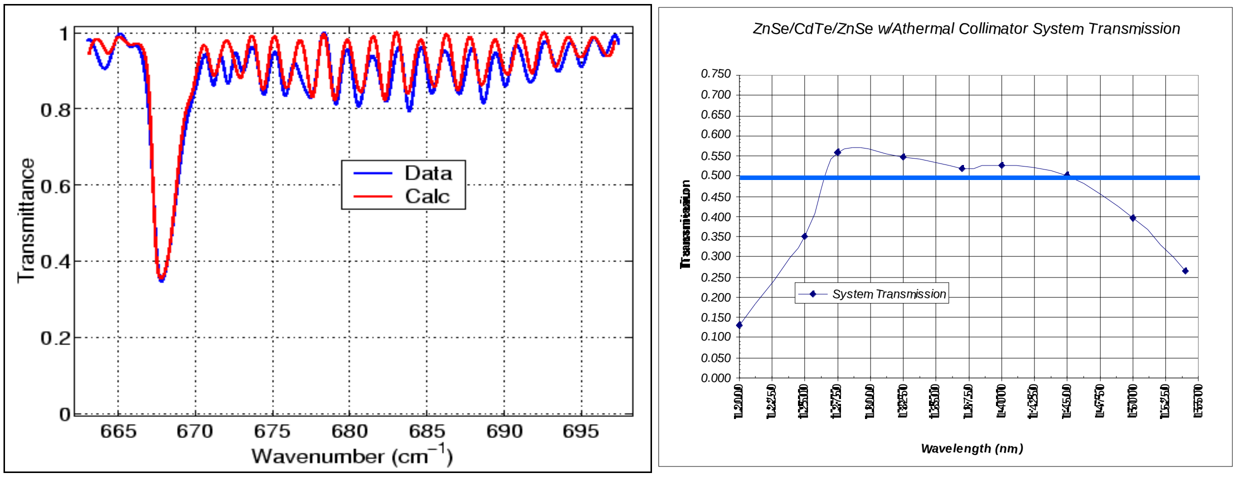


Fig. 5. (left) SIRAS measurements of laboratory air confirmed our spectral resolution was achieved.
(right) Optical Transmission meets requirements across most of the spectrum.

VI. Test Results

Fig. 5 (left) shows the results of the air path test. The data were analyzed for spectral resolution by comparison with a theoretical, 3-m air path atmospheric transmission spectra with varying spectral response widths. The response widths were varied until the resulting convolved modeled atmospheric spectra matched the measured spectra. The results indicate that the SIRAS spectral resolution is 1200 ± 300, or in the range of 900 to 1500. We believe it to be in the range of 900 to 1200 based on the design parameters.

A second key requirement for SIRAS is that the transmission be at least 50% across the spectrum. Measured reflectance and transmission data were compiled from witness samples acquired during the development. The system transmission was calculated and is shown in Fig. 5 (right). Results show that we did not meet our requirements at the short and long wavelength ends. Most of this is attributable to a commercial grade spectral filter that was used to minimize costs. Analysis shows we can meet our requirements with a custom designed filter.

VII. System Configuration Studies

One of the tasks of the SIRAS IIP effort was to determine the potential impact of the technology on future Earth Science Enterprise (ESE) programs. There are at least four possible future ESE programs that would benefit from the technology developed under this IIP, as described below. The biggest advantage in SIRAS over other systems comes from its ability to improve the spatial resolution of these future sounders, allowing more opportunities for clear measurements while observing cloudy scenes. The IIPs are happening early enough to provide technology that will address the “follow-ons” to those missions that perform atmospheric measurements in the IR.

A. AIRS Follow-on

The first potential future application is a follow-on system for the EOS Aqua Atmospheric Infrared Sounder (AIRS) program. AIRS will provide global measurements of water vapor and temperature from LEO at unprecedented resolution and accuracy. AIRS is scheduled for launch in early 2002. SIRAS was originally designed to meet all the requirements of AIRS in a significantly smaller system. We believe this IIP demonstrates key technology allowing that objective to be achieved.

As we learn more about AIRS and assimilation of data by the weather forecasting community, it has become increasingly clear the extent to which clouds degrade the ability to achieve accurate retrievals. We project that future sounding systems will require greatly enhanced spatial resolution. We now have designs for SIRAS that offer a footprint of less than 0.6 km (as compared to AIRS at 13.5 km) without sacrificing SNR. These designs modify the collimator as described above and utilize large-format FPAs. We believe the enhancement to the collimator (front-end optics) to accommodate the wider spatial field of view is a natural advancement of the system using the full potential of the camera (back-end optics). The system is used in “pushbroom” scan mode to preserve the integration time. The drawback of this approach is that the wide scan angle (±49.5°) is not achieved. We conceive that the instrument configuration will have a pointing mirror to allow observations cross-track of desired regions.

B. Advanced Baseline Sounder

The second future application is the Advanced Baseline Sounder (ABS), a planned next generation Geosynchronous infrared atmospheric sounder. The requirements for next generation IR sounding from Geosynchronous orbit can be met with the same SIRAS spectrometer design as that developed for LEO.

	AIRS	SIRAS-L
Size	0.9 m^3	0.13 m^3
Mass	140kg	50 kg
Power	220W	100W
Rate	1.42 Mbps	1.42 Mbps

	GOES	SIRAS-G
Size	0.67 m^3	0.19 m^3
Mass	129 kg	50 kg
Power	125 W	100W
Rate	2.5 kbps	2.5 Mbps

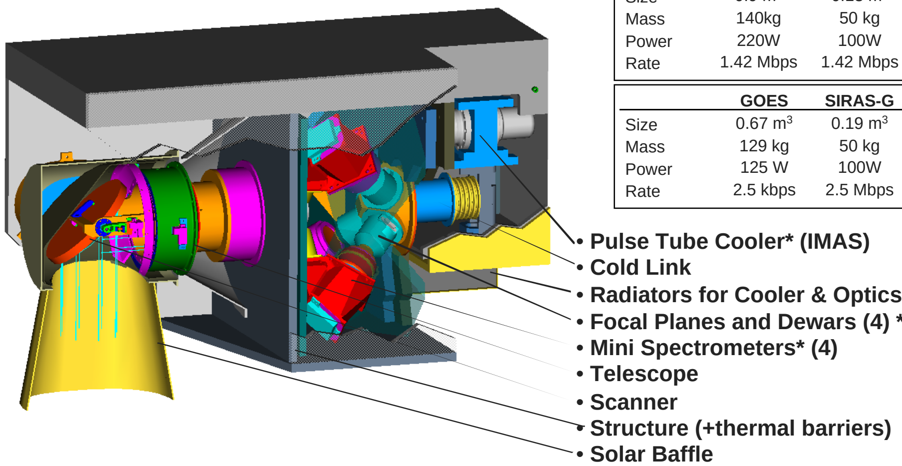


Fig. 6. SIRAS-G is extremely compact and offers all the AIRS performance from GEO.

With the spectrometer 1-mr instantaneous field of view (IFOV), we currently estimate < 10-km resolution with a 4-in (4× magnification) aperture (as shown in Fig. 6) and < 5 km with an 8-in (8× magnification) aperture. The latter is more suitable to the current ABS encircled energy requirements and would result in a somewhat larger front end of the instrument. SIRAS has no moving parts in the spectrometer, requires no transforms to obtain spectra, and uses proven AIRS spectrometer technology and data processing algorithms. The SIRAS concept is much smaller, lighter and uses less power than other proposed future systems for this applications.

Finally, we believe the calibration accuracy and precision will be comparable to AIRS, which has demonstrated exceptional performance in this area.

C. ASTER Follow-on

The third future application that can benefit from the SIRAS technology is for land thermal imaging. Follow-on missions to ASTER will require improved atmospheric correction of the type that can be performed with one of the 4 SIRAS spectrometers. Currently an enhanced spatial resolution instrument to perform ASTER-type observations is being considered for proposal by JPL and MSFC as a future ESSP mission. This proposed ESSP mission, called TRUE, will carry a single modular SIRAS spectrometer of the type developed under the IIP to accompany a larger high-resolution thermal imaging telescope. The SIRAS atmospheric correction system would be of similar spatial resolution to the LEO sounder of approximately < 0.6 km.

D. CO_2 Measurement Mission

Studies at UMBC [3] have determined that it is possible to retrieve atmospheric CO_2 column abundance from the AIRS instrument. The accuracies are limited due to the large spatial footprint of AIRS (13.5 km) and the presence of clouds. The large footprints provide an upper limit on the sensitivity due to the "computational noise" associated with the scene variability. The sensitivity is also limited by the number of cloud-free measurements that can be obtained of the scene. As mentioned above, analysis has shown that the SIRAS can achieve < 0.6 km resolution from LEO, resulting in a considerable reduction in the computational noise as well as a large increase in the number of cloud-free measurements. JPL and UMBC have submitted a proposal for the Instrument Incubator Program to demonstrate the effectiveness of this technique for measurement of CO_2 from an aircraft.

VIII. Summary and Conclusions

JPL and BATC will continue to support technologies that facilitate future atmospheric science measurements of the type made by AIRS. SIRAS provides all the capability of AIRS in a much smaller and lighter package and offers potential to improve the spatial resolution by a factor of approximately 24 in future systems. The IIP has demonstrated the ability of the SIRAS spectrometer to achieve the performance necessary to meet these objectives. The longest wavelength spectrometer was developed and tested for spectral resolution and radiometric throughput. Testing was performed in a thermal vacuum environment and validated the optical and mechanical robustness of the design.

The SIRAS spectrometer has many applications for ESE future missions, including LEO and GEO temperature and humidity sounding, atmospheric correction, and CO_2 measurements. We believe a single-configuration spectrometer suite (4) is possible that will meet all the requirements of these systems. Changes would be required for the instrument telescope (not the spectrometer) and scanning systems in the GEO application. Increased field of view in the spatial direction has not been demonstrated by the front end of the spectrometer (the collimator); however, designs exist that demonstrate this to be feasible. We hope to demonstrate this capability in a future technology demonstration.

From this IIP demonstration, we have advanced the state of the art in 2-dimensional (spectral and spatial) infrared optical designs with high spectral and spatial resolution for ESE applications. We now place demanding requirements on IR long-wavelength FPAs to accommodate these future systems. The basic requirements defined in Table 1 require more than 566 elements in spectrometer 4 in the spectral direction and, depending on the application, we could require from 16 to 256 elements (at 50-µm pitch) in the spatial direction. The information content in the SIRAS spectrometers will also be very high and lead to large data rates. As we enter the new millennium, we will find it a challenge to accommodate the large amounts of information that the technology can provide, yet be rewarded by the improvements in resolution and accuracies of our observations.

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